Performance of a High-Fidelity 4 kW-Class Engineering Model PPU and Integration with the HiVHAc System

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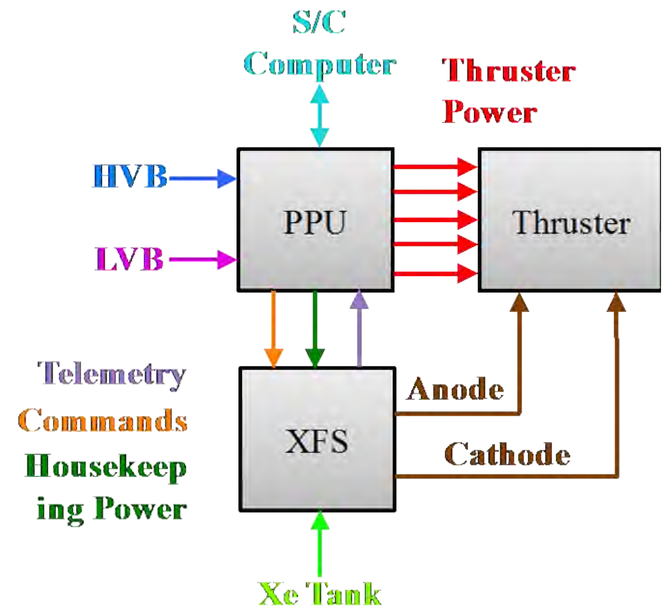
Background: HiVHAc System

- NASA GRC is leading the technology development activities for the High Voltage Hall Accelerator (HiVHAc) propulsion system

- Substantial cost and performance benefits for certain types of Discovery-class science missions compared to SOA ion and Hall thruster systems

- The HiVHAc system consists of three elements:
  - Thruster
  - XFS
  - PPU

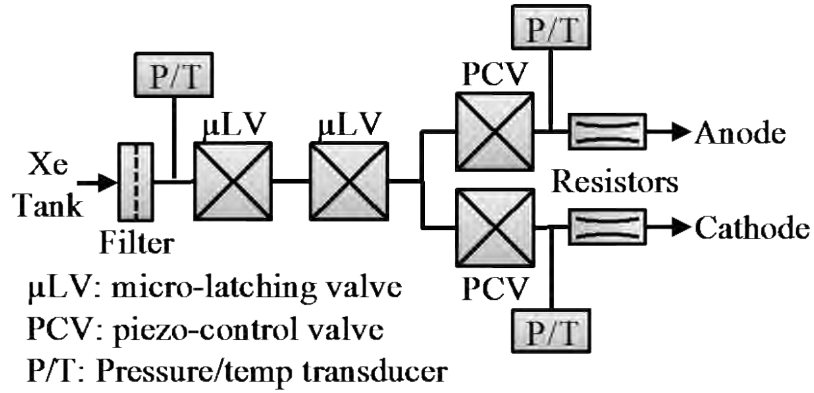


Background: HiVHAc Thruster

HiVHAc EDU-2 Thruster

- Latest version of the HiVHAc thruster is the engineering development unit (EDU-2) developed by GRC and Aerojet
  - 3.9 kW discharge power
  - 2,700 s specific impulse at discharge voltage of 650 V
  - 58% efficiency
  - In-situ self-regulating discharge channel replacement mechanism
- Kamhawi, H., et al., "Performance and Environmental Test Results of the High Voltage Hall Accelerator Engineering Development Unit," AIAA-2012-3854, 48th AIAA Joint Propulsion Conference, Atlanta, Georgia, July 2012.

Background: Xenon Feed System



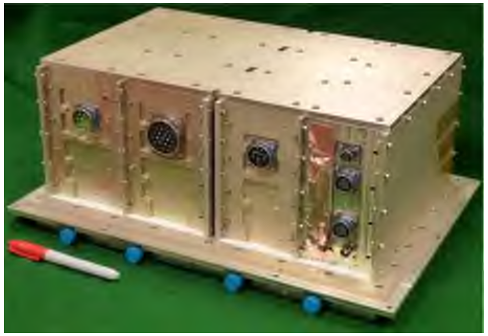
- Xenon flow control module (XFCM) was developed by VACCO Industries
- Joint effort between NASA and the Air Force Research Laboratory (AFRL) as a lightweight propellant flow control alternative for electric propulsion
- Inlet pressure range = 10 to 3,000 psia
- Flow range = 0 to 160 sccm
- Mass = 1.25 kg
- Dimensions = 19.5 x 7.0 x 7.5 cm
- Power < 1 W
- Flight qualification completed in 2012
- Dankanich, J., et al., “Advanced Xenon Feed System (AXFS) Development and Hot-fire Testing,” 45th AIAA Joint Propulsion Conference, AIAA 2009-4910, Denver, Colorado, August 2009.

Background: CPE/HiVHAc PPU

- Developed by Colorado Power Electronics (CPE) in Fort Collins, Colorado, with funding from NASA'S Small Business Innovative Research (SBIR) Program
- Four design iterations have been completed
  - Breadboard discharge module
  - Brassboard #1 demonstrated power converters
  - Brassboard #2 refined the electrical and mechanical design and made it more flight-like
  - Engineering model improved manufacturability and included a digital control interface unit (DCIU), electronics for XFCM, and rad-hard MOSFETs on one of two discharge modules
- All units where integrated with HiVHAc thrusters at GRC
- Brassboard units were tested for thousands of hours in vacuum
- EM unit performance was thoroughly characterized in vacuum

Breadboard Discharge Module

Brassboard PPU #1

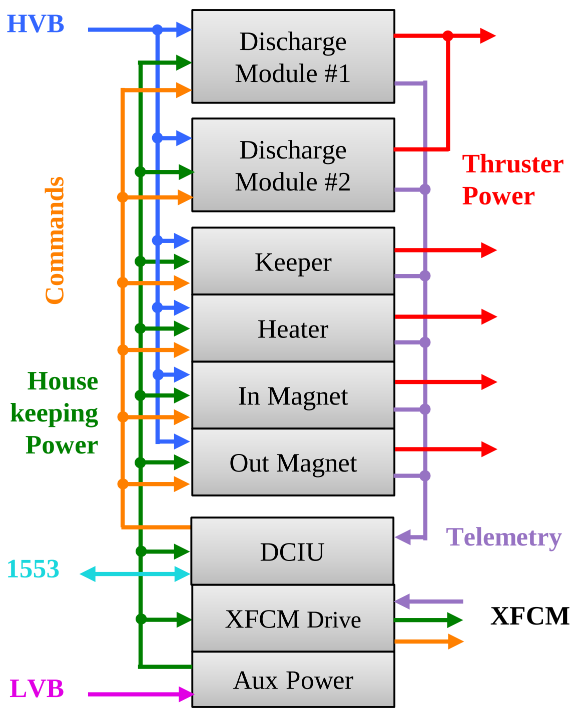


Brassboard PPU #2

EM PPU

CPE/HiVHAc EM PPU

EM PPU	Discharge	Magnets (2)	Keeper	Heater
Output Voltage	200 – 700 V	2 – 10 V	5 – 40 V	1 – 15 V
Output Current	1.4 – 15 A	1 – 5 A	1 – 4 A	3.5 – 10 A
Output Power Max	4 kW	50 W	80 W	150 W
Regulation Mode	Voltage or Current	Current	Current	Current
Output Ripple	≤ 5%			
Line/Load Regulation	≤ 2%			
Input Voltage	80 – 160 V (main) and 24 – 34V (housekeeping)			



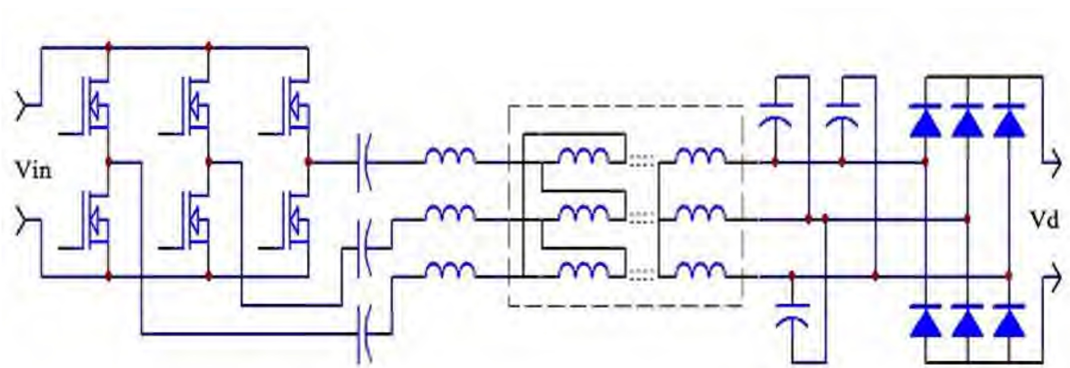
- Modular design
  - Two discharge modules
  - One ancillary module
  - One DCIU module
- High voltage bus (HVB) input
- Low voltage bus (LVB) input
- MIL-STD-1553

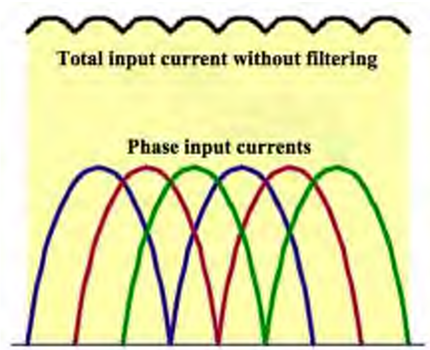
- Thruster Power
  - Discharge
  - Inner Magnet
  - Outer Magnet
  - Keeper
  - Heater

- XFCM
  - Power
  - Control
  - Telemetry

Discharge Modules

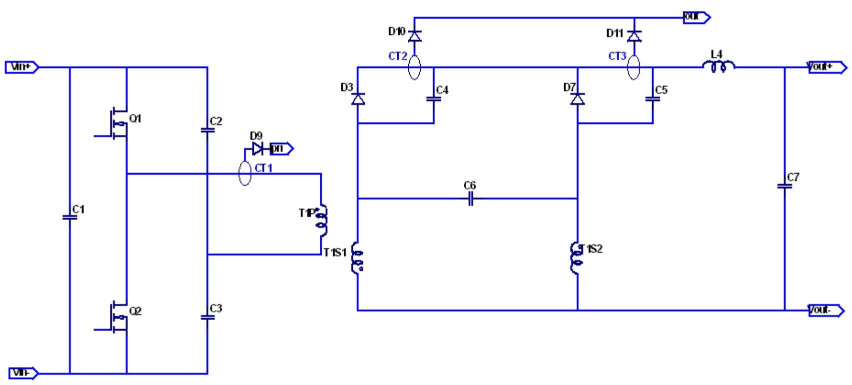
- 3-phase LLC resonant converter
  - Wide range of operation
  - Very low filter requirements
- Two discharge modules operate in parallel
- Either module can operate as master and limit the current of the other module
- Output voltage and current regulation loops
- Discharge modules can deliver full power (4 kW) and any output voltage from 250 to 700 V and any input voltage
- Piñero, L., et at., "Integration Testing of a Modular Discharge Supply for NASA's High Voltage Hall Accelerator Thruster," 31st International Electric Propulsion Conference, IEPC-2009-275, Ann Arbor, Michigan, September 2009

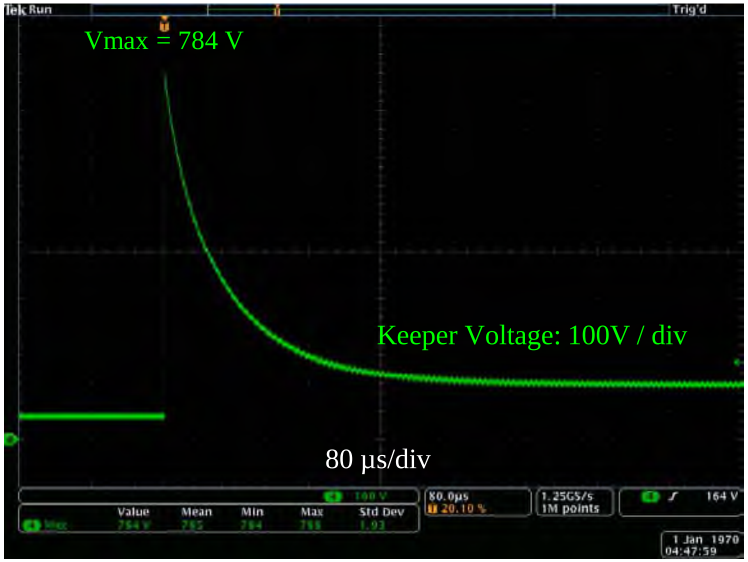




Ancillary Module

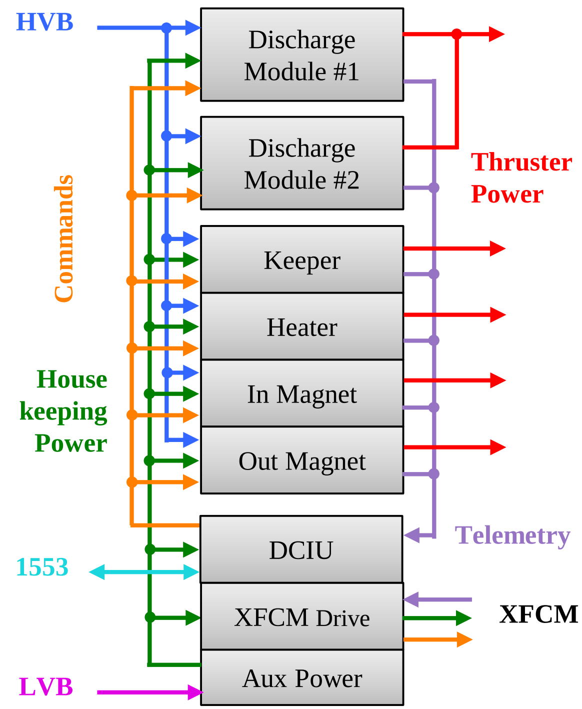
- Power supplies beside discharge needed for thruster
  - Inner magnet supply
  - Outer magnet supply
  - Keeper supply with pulse ignitor
  - Heater supply
- Single-phase resonant converters
- Similar power converter design
- Inner and outer magnet supplies are same design





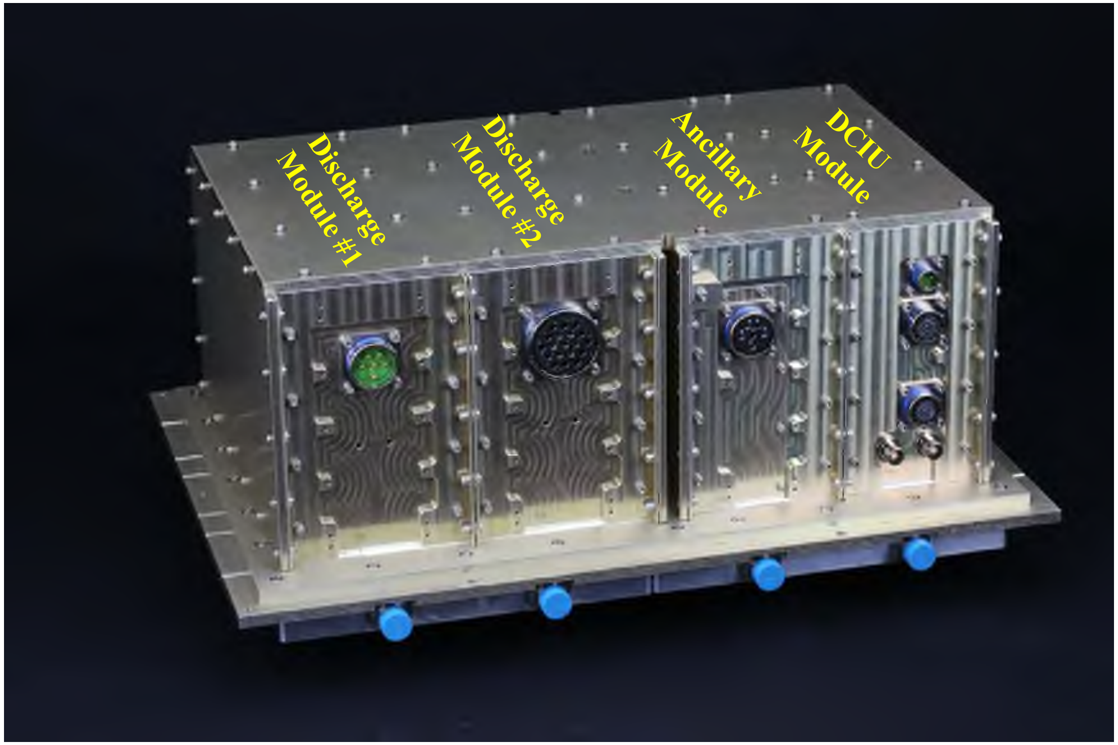
DCIU Module

- DCIU
  - Implemented by a reprogrammable field programmable gate array (FPGA)
  - Receives commands and transmits telemetry to control computer through a MIL-STD-1553B interface
  - Processes telemetry from power supplies and XFCM
  - Automatically controls the system
    - ✓ Cathode conditioning
    - ✓ Cathode ignition
    - ✓ Discharge start-up
    - ✓ Steady-state (discharge current close-loop control)
    - ✓ Throttle
    - ✓ Shutdown
  - Control parameters are programmable
    - ✓ Thresholds
    - ✓ Limits
    - ✓ Ramp rates
    - ✓ Delays and durations
  - Monitors operation and safes system in case of fault
  - Includes manual-mode operation for diagnostics



- Auxiliary power supply
  - Uses power from a low voltage bus (LVB) input to generate auxiliary or housekeeping power for the power supplies, XFCM, and DCIU
- XFCM drive
  - Drivers for micro-latching and piezo-control valves
  - Power for temperature and pressure transducers

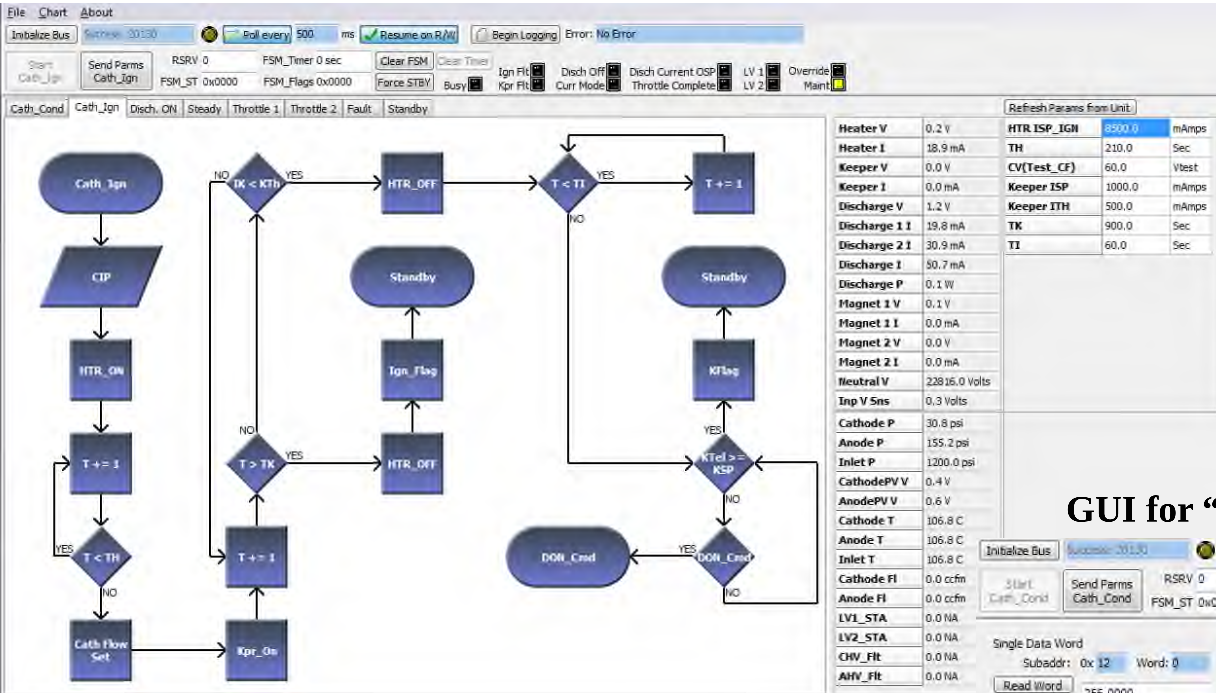
CPE/HiVHAc EM PPU



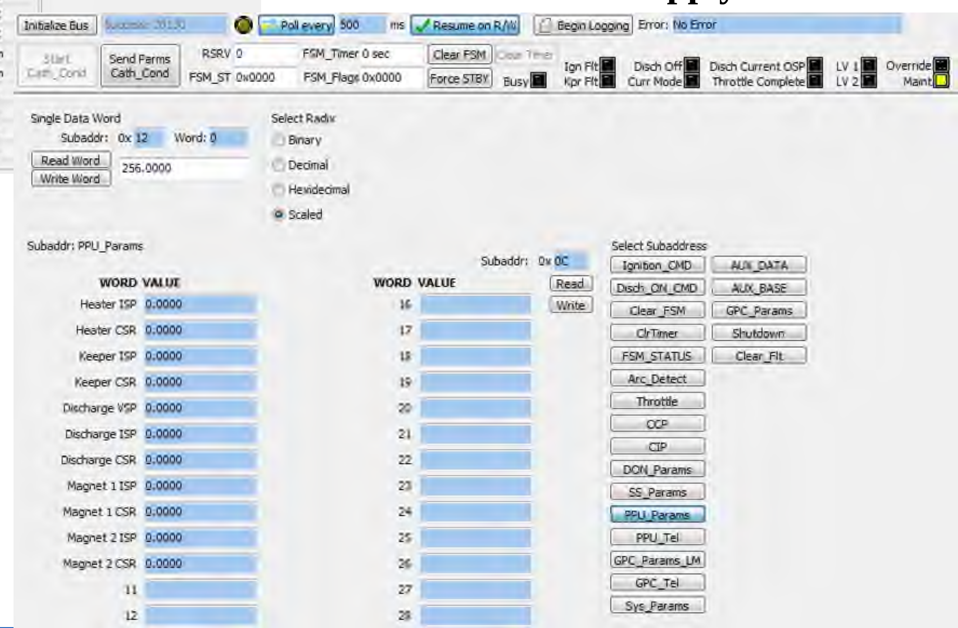
- Modular design
- Dimensions = 38.6 x 23.2 x 16.3 cm
- Mass = 15.6 kg

System Control GUI

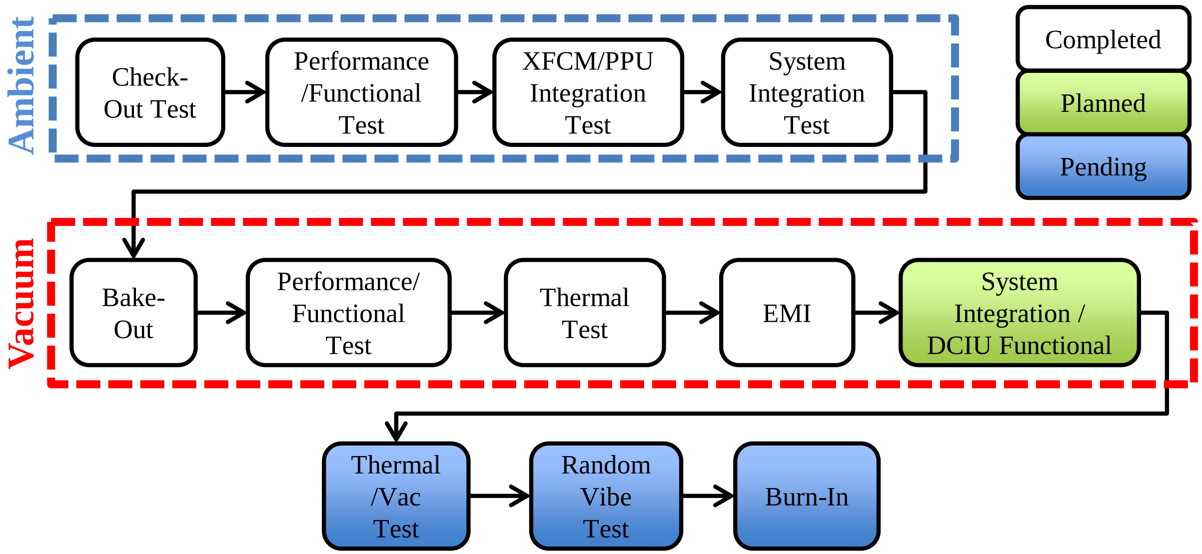
GUI for Cathode Ignition Sequence in "Auto-Mode" Control



GUI for "Manual-Mode" Power Supply Control

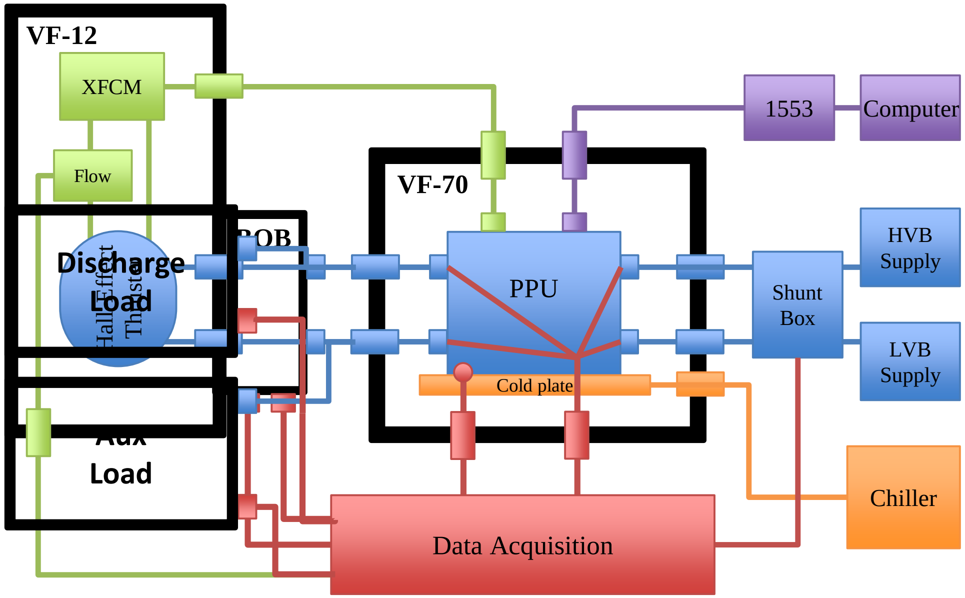


EM PPU Test Flow



- Functional and performance tests were conducted in air and vacuum
- Vacuum performance tests were conducted at baseplate operational limits of -20 and 50˚C
- Integration with thruster and XFCM
- EMI characterization was conducted per MIL-STD-461C (CE01 and CE03)

EM PPU Test Setup



- VF-70
  - Dedicated for PPU testing
  - 0.6-m diameter by 1-m long
  - < $1\text{x}10^{-6}$ while operating PPU
  - Located next to VF-12
- VF-12
  - 3-m diameter by 10-m long
  - Cryo-pumped
  - $1\text{x}10^{-5}$ Torr while operating thruster

Operating Conditions

Discharge Voltage	Discharge Current	Magnet Current	Keeper Current	Thruster Power	HVB Voltage	LVB Voltage
200 V	1.4 A	2.4 A	1.0 A	0.31 kW	80, 120, 160 V	24, 28, 34 V
300 V	1.7 A	2.9 A	1.0 A	0.55 kW	80, 120, 160 V	28 V
400 V	2.5 A	2.8 A	1.0 A	1.03 kW	80, 120, 160 V	28 V
500 V	3.0 A	3.7 A	1.0 A	1.55 kW	80, 120, 160 V	28 V
600 V	2.6 A	4.0 A	1.0 A	1.62 kW	80, 120, 160 V	28 V
650 V	2.3 A	4.0 A	1.0 A	1.55 kW	80, 120, 160 V	28 V
200 V	7.5 A	4.0 A	1.0 A	1.56 kW	80, 120, 160 V	28 V
300 V	6.9 A	3.5 A	1.0 A	2.12 kW	80, 120, 160 V	24, 28, 34 V
400 V	7.4 A	2.4 A	1.0 A	2.99 kW	80, 120, 160 V	28 V
500 V	7.7 A	3.5 A	1.0 A	3.90 kW	80, 120, 160 V	28 V
600 V	6.5 A	2.7 A	1.0 A	3.93 kW	80, 120, 160 V	28 V
650 V	5.9 A	2.7 A	1.0 A	3.89 kW	80, 120, 160 V	24, 28, 34 V

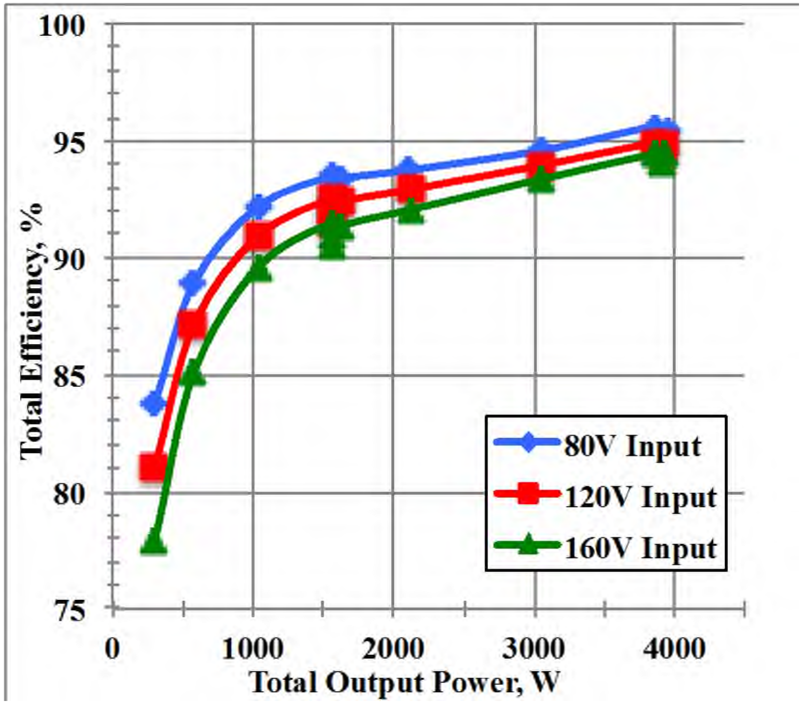
- Operating conditions of resistive load cover entire operating range of the HiVHAc thruster
- Power supplies were independently tested in some cases to cover the actual operating range of the power supply (i.e. 200 V / 15 A)
- PPU as operated at the baseplate operational limits of -20 to 50˚C

CPE/HiVHAc EM PPU Performance

	Specification	Test Results		Test Conditions
Telemetry Accuracy	≤ 2% of FS	Discharge ≤ 1.0%	Keeper ≤ 2.7%	Over throttling range
		Magnet ≤ 1.5%	Heater ≤ 2.0%	
Set point Accuracy	≤ 2% of FS	Discharge < 0.1%	Keeper ≤ 2.5%	Over throttling range
		Magnet ≤ 0.8%	Heater ≤ 1.7%	
Line Regulation	≤ 2 %	Discharge ≤ 0.01%	Keeper ≤ 3.2%	Over operating range
		Magnet ≤ 0.8%	Heater ≤ 0.7%	
Load Regulation	≤ 2 %	Discharge ≤ 0.05%	Keeper ≤ 0.8%	Over operating range
		Magnet ≤ 0.8%	Heater ≤ 1.9%	
Efficiency	≥ 95 % at FP	Discharge: 86–96%	Keeper: 47–80%	Over operating range
		Magnet: 57–86%	Heater: 57–87%	
Output Ripple	≤ 5 %	Discharge ≤ 0.7%	Keeper ≤ 3.3 %	Over operating range
		Magnet ≤ 0.8%	Heater ≤ 1.0%	
Transient Response	n/a	Discharge ≤ 8 ms	Keeper ≤ 4 ms	No-load to full power
		Magnet ≤ 10 ms	Heater ≤ 8 ms	
Temperature Range	-20 to 50˚C	-20 to 50˚C		

- Electrical specifications were met with margin with exception of the keeper telemetry accuracy and regulation
- Improvements for these circuits have been developed and will be implemented in the next design iteration.

CPE/HiVHAc EM PPU Efficiency

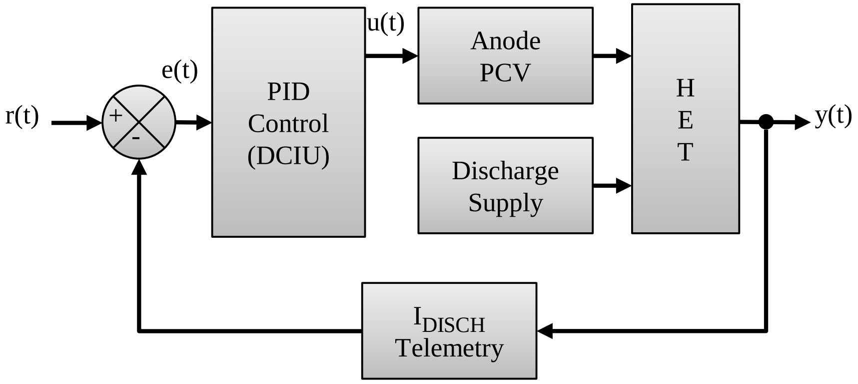


- Efficiency at full power was 95%
- Efficiency was > 90% from 1 to 4 kW
- Variation over entire input voltage range was approximately 0.5%
- Variation over entire temperature range was approximately 0.5%

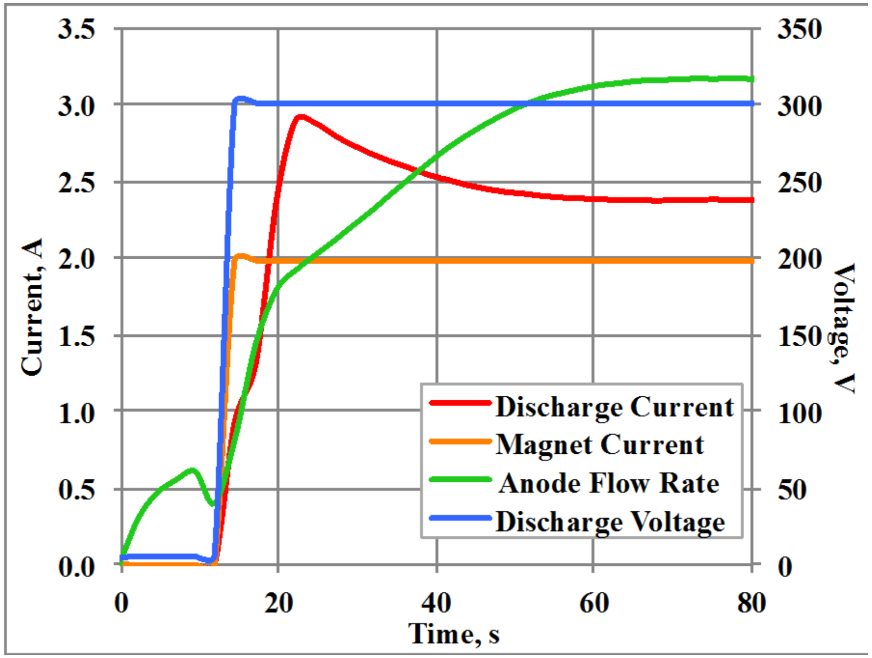
System Integration Test

- Integrate the PPU with the XFCM
  - Demonstrate control of latching valves
  - Demonstrate control of the piezo-control valve
  - Demonstrate telemetry was received

- Integrate the PPU, XFCM and thruster
  - Demonstrate cathode ignition
  - Demonstrate discharge start-ups
    - ✓ "Hard" mode
    - ✓ "Glow" mode
  - Demonstrate close-loop on discharge current
    - ✓ Steady-state
    - ✓ Throttling



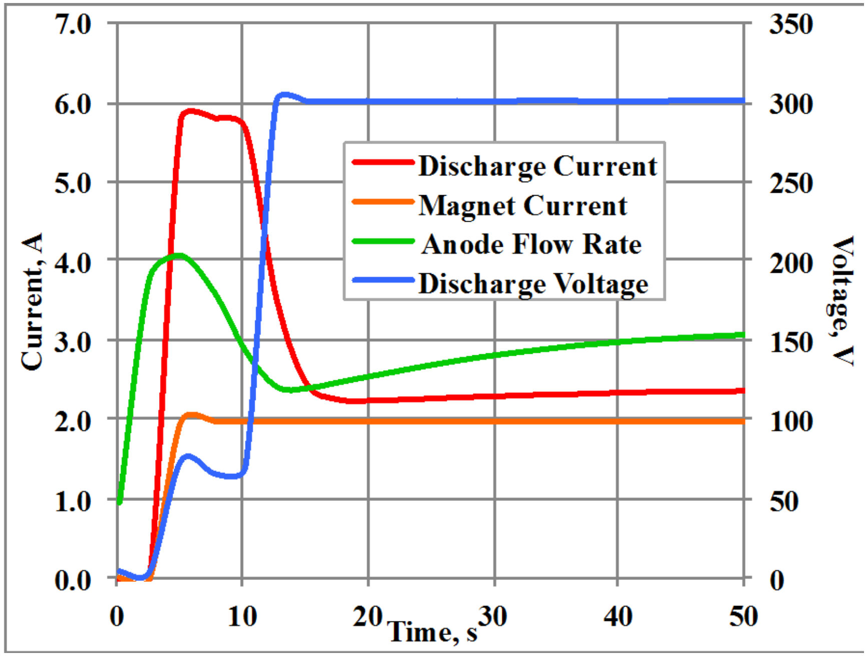
Discharge Start-Up



"Hard" Mode

- T = 0s
  - Cathode ignited and operating off keeper supply
  - Anode PCV OPEN command
- $0 < T \leq 12s$
  - Anode flow ramps up
- T = 12s
  - Discharge and magnet supplies ON command
- $12s < T \leq 22s$
  - Discharge current ramps up
  - ~ 20% overshoot
- $22s < T \leq 60s$
  - Close-loop adjusts flow to take discharge current to setpoint
- The overshoot discharge current shows the hysteretic behavior of the PCV
  - Can be minimized by optimizing the PID controller parameters
- Start up timing and magnitudes can be changed through sequence parameters

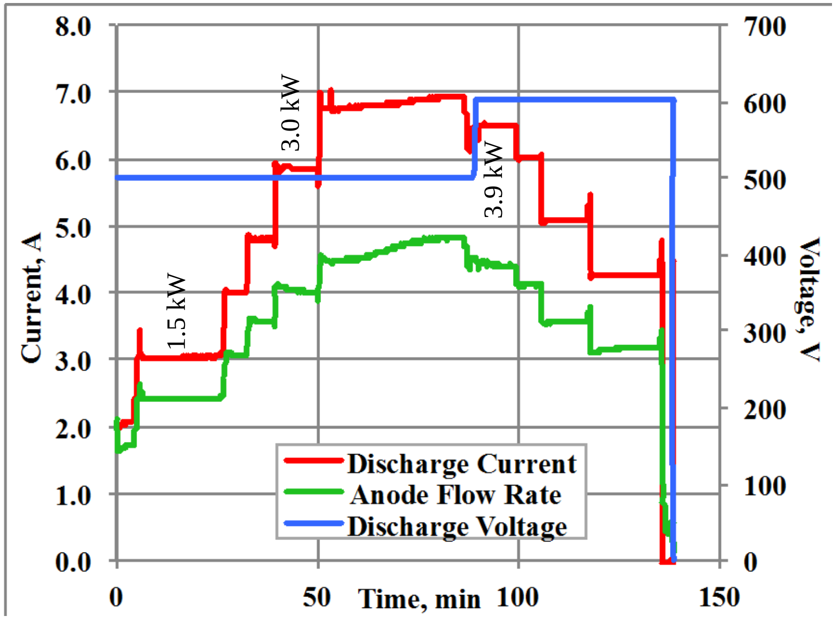
Discharge Start-Up

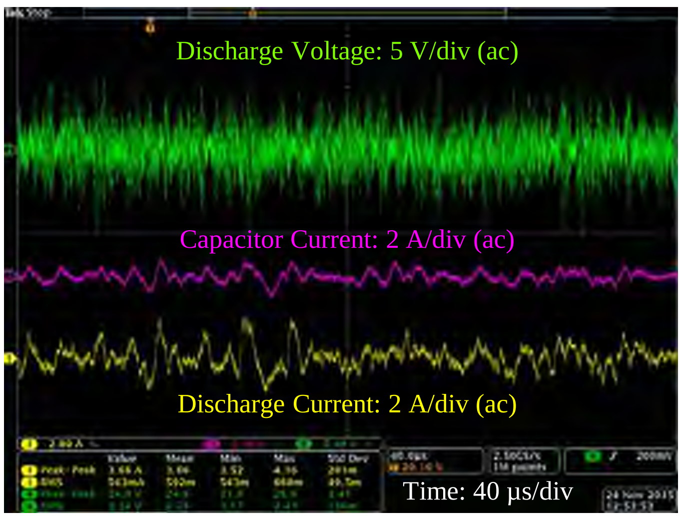


"Glow" Mode

- T = 0s
  - Cathode ignited and operating off keeper supply
  - Anode PCV OPEN command
- $0 < T \leq 3s$
  - Anode flow ramps up
- T = 3s
  - Discharge and magnet supplies ON command
- $3s < T \leq 7s$
  - Discharge current ramps up
  - Discharge supply operating in current-mode at current limit setpoint
- $7s < T \leq 12s$
  - Close-loop ramps down flow rate to take discharge current to setpoint
  - ~20% undershoot
- $12s < T \leq 50s$
  - Close-loop adjusts flow to take discharge current to setpoint
- The overshoot discharge current shows the hysteretic behavior of the PCV
  - Can be minimized by optimizing the PID controller parameters
- Start up timing and magnitudes can be changed through sequence parameters

Throttling





- T = 0 min
  - Thruster operating at approximately 500 V / 2.0 A / 1.0 kW
- 0 < T ≤ 50 min
  - Discharge current increased approximately 1 A increments to 3.5 kW
- 50 min < T ≤ 90 min
  - Small adjustments in current
- T = 90 min
  - Discharge current reduced to ~ 6.5 A
  - Discharge voltage increased to 600 V
  - Thruster operating at full power of 3.9 kW
- 90 min < T ≤ 140 min
  - Thruster throttled down to 1.8 kW
- T = 140 min
  - Thruster off
- The overshoot and undershoots in discharge current at transitions can be minimized by optimizing the parameters of the PID controller
- Discharge oscillations were nominal during test
- PPU was also successfully integrated with a SPT-140 using the same test setup
  - Kamhawi, H., et al., "Integration Test of the 4 kW-Class HiVHAc PPU with the HiVHAc and the SPT-140 Hall Effect Thrusters," AIAA-2016-4943.

Future Plans

- Prototype Demonstration Unit (PDU) PPU
- Next iteration of PPU based on EM PPU electrical and mechanical design
- Output specifications were changed to enable operation of other commercial thrusters
  - Discharge power
  - Magnet voltage and current
  - Heater voltage and current
- Input voltage range was changed to satisfy power requirements of commercial spacecraft busses and NASA missions
- Additional functionality:
  - Magnet reversal
  - Independent discharge module control
  - XFCM inlet heater power to enable high flow rate
  - Health status flags
  - Safety interlocks and lockouts
  - Telemetry
    - ✓ Input
    - ✓ Discharge ripple
  - Correct minor issues identified during EM PPU testing

PDU PPU	Discharge	Magnets (2)	Keeper	Heater
Output Voltage	200 – 700 V	2 – 20 V	5 – 40 V	1 – 13 V
Output Current	1.4 – 15 A	1 – 7.5 A	1 – 2 A	3.5 – 21 A
Output Power Max	4.5 kW	108 W	80 W	210 W
Regulation Mode	Voltage or Current	Current	Current	Current
Output Ripple	≤ 5%			
Line/Load Regulation	≤ 2%			
Input Voltage	68 – 140 V (main) and 24 – 34V (housekeeping)			

- All parts will have flight equivalents or will have path to flight qualification
- Will be built using flight processes and procedures
- Analyses:
  - Stress
  - Thermal
  - Structural
  - Worst-case
  - Radiation assessment

Conclusions

- The CPE/HiVHAc EM PPU was successfully tested
- Most electrical requirements were met with margin
- Total efficiency as high as 95% at full power was measured
- Performance was measured at operating temperature extremes of -20 and 50˚C
- Integrated with VACCO XFCM and HiVHAc thruster to demonstrate close-loop control on discharge current with anode flow
- Successfully demonstrated ignitions, start ups, and throttling
- A PDU PPU is under development will have additional functionality, will better capture NASA and commercial needs, and will get the design closer to flight-qualification.

Questions?